

An Indirect Handle on the Down-Quark Yukawa Coupling

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ABSTRACT: To measure the Yukawa couplings of the up and down quarks, $Y_{u,d}$, seems to be far beyond the capabilities of current and (near) future experiments in particle physics. By performing a general analysis of the potential misalignment between quark masses and Yukawa couplings, we derive predictions for the magnitude of induced flavor-changing neutral currents (FCNCs), depending on the shift in the physical Yukawa coupling of first-generation quarks. We find that a shift of -100% in the down-quark Yukawa Y_d would generically result in ds transitions in conflict with Kaon physics. This could already be seen as evidence for a non-vanishing direct coupling of the down quark to the newly discovered Higgs boson. The *non-observation* of certain, already well-constrained, processes is thus turned into a powerful indirect measure of physical parameters of the effective Standard-Model, which are so far basically unconstrained from experiment and extremely challenging to access with other methods. In particular, we can already deduce that Y_d should vary at most by $\sim 50\%$ from its Standard Model value, barring an alignment of new physics effects with the SM Yukawa couplings. Such an (orthogonal) alignment scenario is however in general much easier to test at the LHC. Similarly, improvements in limits on FCNCs in the up-type quark sector can lead to valuable information on the physical Yukawa coupling of the up-quark.

1 Introduction

While the LHC and a future linear collider are expected to determine the Yukawa couplings of the heavy third-generation fermions at the $\mathcal{O}(\%)$ level, see e.g. [1, 2], the diagonal Yukawa couplings of the first generation seem to be out of our direct reach in the near future. In this paper, we will demonstrate how we can nevertheless gain valuable information about the possible size of the up and in particular the down-quark Yukawa couplings in the mass basis, $Y_{u,d}$, in an indirect way. For that purpose we employ the fact that modifications of the Standard-Model (SM) Yukawa matrices that change Y_d generically also induce modifications in the off-diagonal entries in the mass basis and thus lead to flavor-changing neutral currents (FCNCs). In particular, tree-level Higgs exchange can now mediate meson-antimeson oscillations. These are however severely constrained from flavor-physics experiments, see e.g. [3].

2 Setup

We want to examine a possible misalignment between the quark-mass and Yukawa matrices. In order to keep the discussion general and to respect gauge invariance, we introduce this misalignment via the $D = 6$ operators

$$\mathcal{L}_6^Y = \frac{1}{v^2} \left((\Phi^\dagger \Phi) \bar{q}_L \mathbf{C}_u \Phi^c u_R + (\Phi^\dagger \Phi) \bar{q}_L \mathbf{C}_d \Phi d_R \right). \quad (2.1)$$

Here, Φ denotes the Higgs doublet, which we will parametrize in unitary gauge as $\Phi = 1/\sqrt{2} (0, h + v)^T$, where v is the vacuum expectation value $\langle \Phi \rangle = 1/\sqrt{2} (0, v)^T$, h is the physical Higgs field, and q_L, u_R, d_R are the chiral SM-quark doublet and singlets, each 3-vectors in flavor space. Inserting this decomposition of the Higgs doublet into (2.1) as well as into the SM Yukawa terms with couplings $\hat{\mathbf{Y}}_{\text{SM}}^{u,d}$, we arrive at the fermion masses and Higgs couplings in the flavor basis

$$\mathcal{L} \supset -u_L \left(\hat{\mathbf{M}}^u + \frac{1}{\sqrt{2}} \hat{\mathbf{Y}}^u h \right) u_R - d_L \left(\hat{\mathbf{M}}^d + \frac{1}{\sqrt{2}} \hat{\mathbf{Y}}^d h \right) d_R, \quad (2.2)$$

where $\hat{\mathbf{Y}}^{u,d} = \hat{\mathbf{Y}}_{\text{SM}}^{u,d} + \frac{3}{2} \mathbf{C}_{u,d}$ and $\hat{\mathbf{M}}^{u,d} = \frac{v}{\sqrt{2}} (\hat{\mathbf{Y}}_{\text{SM}}^{u,d} + \frac{1}{2} \mathbf{C}_{u,d}) = \frac{v}{\sqrt{2}} (\hat{\mathbf{Y}}^{u,d} - \mathbf{C}_{u,d})$ are now independent parameters.

In this article, we focus on the light quarks and compare our predictions with the strongest constraints on corresponding quark FCNCs available to date. The only “assumption” we make is that the Wilson coefficients $\mathbf{C}_{u,d}$ exhibit an anarchic flavor structure, in a sense that they feature arbitrary complex entries, up to a certain allowed scale. While a full comprehensive channel-by-channel analysis, including a detailed survey of the impact of further assumptions we could make on the structure of the dimension-6 operators (2.1), as well as an extension to the lepton (and heavy quark) sector, would be interesting, here we just want to point out the predictive power of the approach. A corresponding global analysis is left for future work [4].

Let us nevertheless already note that abandoning the chosen anarchic approach by assuming a special flavor structure like an (approximate) alignment of the $D = 6$ operators

with the Yukawa matrices, $\hat{\mathbf{M}}^{u,d} \propto \hat{\mathbf{Y}}^{u,d}$, results in a scenario that can easily be accessed and excluded directly at the LHC. In fact, such an alignment would lead to (approximately) the same relative shift in the down and bottom Yukawa couplings. Our method thus offers a complementary indirect access to the diagonal Yukawa coupling of light quarks, given that the LHC finds no large deviation in the bottom Yukawa. In that case, which excludes large contributions from a potentially flavor-aligned deviation in the Yukawa couplings (evading FCNCs), our approach has a high power in constraining Y_d . In the following we will indeed assume the absence of sizable corrections in Y_b of $> \mathcal{O}(20\%)$ and then our predictions can be considered generic.

We thus start from arbitrary complex Yukawa matrices $\hat{\mathbf{Y}}^{u,d}$ in the flavor basis and introduce a misalignment with the mass matrices $\hat{\mathbf{M}}^{u,d}$ via the coefficients of the anarchic $D = 6$ operators $\mathbf{C}_{u,d}$, see (2.1) and (2.2). The only restriction we impose on $\hat{\mathbf{M}}^{u,d}$ is that they reproduce the correct mass eigenvalues and the CKM matrix after diagonalization, *i.e.*,

$$\mathbf{U}_L^d = \mathbf{U}_L^u \mathbf{V}_{\text{CKM}}, \quad (2.3)$$

where

$$\hat{\mathbf{M}}^d = \mathbf{U}_L^d \text{diag}(m_d, m_s, m_b) \mathbf{U}_R^{d\dagger}, \quad \hat{\mathbf{M}}^u = \mathbf{U}_L^u \text{diag}(m_u, m_c, m_t) \mathbf{U}_R^{u\dagger}. \quad (2.4)$$

The Higgs-coupling matrices in the physical basis $\mathbf{Y}^{u,d}$ are then obtained via

$$\mathbf{Y}^d = \mathbf{U}_L^{d\dagger} \hat{\mathbf{Y}}^d \mathbf{U}_R^d \quad (2.5)$$

and

$$\mathbf{Y}^u = \mathbf{U}_L^{u\dagger} \hat{\mathbf{Y}}^u \mathbf{U}_R^u = \mathbf{V}_{\text{CKM}} \mathbf{U}_L^{d\dagger} \hat{\mathbf{Y}}^u \mathbf{U}_R^u. \quad (2.6)$$

It is just the diagonal (1,1) entries of these Higgs couplings $Y_{u,d} \equiv (\mathbf{Y}^{u,d})_{11}$, that we want to constrain from experimental input in the following.

It is important to note that in general one basis for the mass matrices is as good as the other, and only the misalignment between $\hat{\mathbf{M}}^u$ and $\hat{\mathbf{M}}^d$ is physically observable through the CKM matrix. In consequence, it seems reasonable to assume the most general modifications of the SM values for the Yukawa couplings in the original basis. In particular, in an anarchic approach, it would be unnatural for $\mathbf{C}_{u,d}$ to be diagonal in the same basis as $\hat{\mathbf{Y}}_{\text{SM}}^{u,d}$. In the following section we will present our numerical results. We will first employ arbitrary complex numbers in the range $v/\sqrt{2}|(\mathbf{C}_{u,d})_{ij}| = [0, 5]$ MeV, evaluated at the low scale of the experiments, and demonstrate the correlation between $Y_{u,d}$ and FCNCs. To show that our obtained constraints on $Y_{u,d}$ from flavor-physics experiments are to good approximation insensitive to our assumptions for the Wilson coefficients, we will study two further scenarios. In the first we consider a larger scale $v/\sqrt{2}|(\mathbf{C}_{u,d})_{ij}| = [0, 0.1]$ GeV and in the second we only put $v/\sqrt{2}|(\mathbf{C}_{u,d})_{1,1}| = [0, 5]$ MeV, and the other entries vanishing, in order to demonstrate that we do not feed in special off-diagonal transitions “by hand”.

3 Results

In Figure 1, we show the flavor changing combination of couplings $|(\mathbf{Y}^d)_{13}(\mathbf{Y}^d)_{31}|$ in dependence on the absolute value of the ratio of the physical down-quark Yukawa coupling

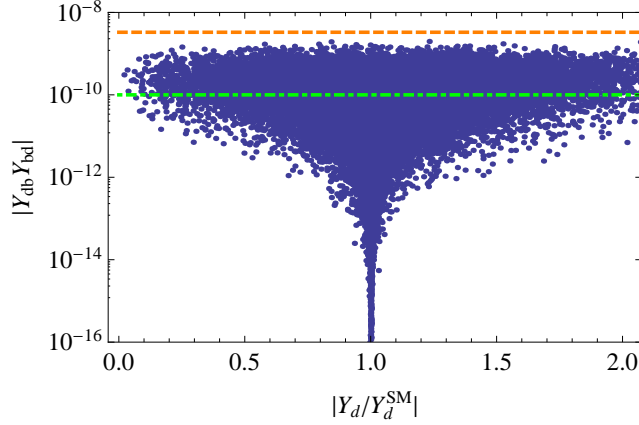


Figure 1. Predictions for the correlation between the off-diagonal transition $|(\mathbf{Y}^d)_{13}(\mathbf{Y}^d)_{31}|$ and $|Y_d/Y_d^{\text{SM}}|$. The current experimental constraint from B_d^0 oscillations is given as an orange dashed line, while a potential experimental improvement by around an order of magnitude is depicted as a green dot-dashed line. See text for details.

Y_d and its value in the SM (with $\mathbf{C}_{u,d} = \mathbf{0}$), $Y_d^{\text{SM}} = m_d \sqrt{2}/v$. Here and in the following we scan the parameterspace uniformly in the complex plane within $|(\mathbf{C}_{u,d})_{ij}| = [0, 5]$ MeV, fixing $\mathbf{Y}_{\text{SM}}^{u,d}$ in an agnostic way that reproduces the correct quark masses and mixings. We note that the crucial lower contour of the scatter plots is to good approximation independent of continuous changes of the range of the parameters, see below. It should nevertheless be stressed that the analysis is meant to examine the general picture and does not take into account all fine-tuned parameterpoints that might be possible. We also give the experimental upper limit on the corresponding off-diagonal Yukawa couplings from flavor physics (B_d^0 oscillations) as presented in [5], $|(\mathbf{Y}^d)_{13}(\mathbf{Y}^d)_{31}|_{\text{exp}} < 3.3 \times 10^{-9}$, as an orange dashed line (see [3] for the corresponding measurements).

One can clearly see that already deviations of the order of 10% in Y_b lead generically to non-negligible flavor changing effects of $|(\mathbf{Y}^d)_{13}(\mathbf{Y}^d)_{31}| > 10^{-12}$ which are however not yet excluded by experiment. A vanishing Y_d would on the other hand result in $|(\mathbf{Y}^d)_{13}(\mathbf{Y}^d)_{31}| > 10^{-10}$. So while with current data on B_d^0 oscillations, one can not yet discard the $Y_d = 0$ hypothesis, a modest experimental improvement in the limit of around one order of magnitude to $|(\mathbf{Y}^d)_{13}(\mathbf{Y}^d)_{31}|_{\text{exp}} < 10^{-10}$, depicted by the green dot-dashed line, could already strongly disfavor the $Y_d = 0$ hypothesis. However, we conclude that current limits on B_d^0 oscillations are not yet capable of constraining Y_d in an interesting range of modest deviations from the SM.

This situation changes when we take into account Kaon physics. In the left (right) panel of Figure 2, we show the magnitude of the real part (imaginary part) of the squared ds transitions $|\text{Re}[(\mathbf{Y}^{d*})_{12}(\mathbf{Y}^d)_{21}]|$, $|\text{Im}[(\mathbf{Y}^{d*})_{12}(\mathbf{Y}^d)_{21}]|$ versus the absolute value of the ratio of the physical down-quark Yukawa coupling Y_d over Y_d^{SM} . We also give the experimental upper limit on the corresponding off-diagonal Yukawa couplings from Kaon physics, $|\text{Re}[(\mathbf{Y}^{d*})_{12}(\mathbf{Y}^d)_{21}]|_{\text{exp}} < 5.6 \times 10^{-11}$, $|\text{Im}[(\mathbf{Y}^{d*})_{12}(\mathbf{Y}^d)_{21}]|_{\text{exp}} < 2.8 \times 10^{-13}$.

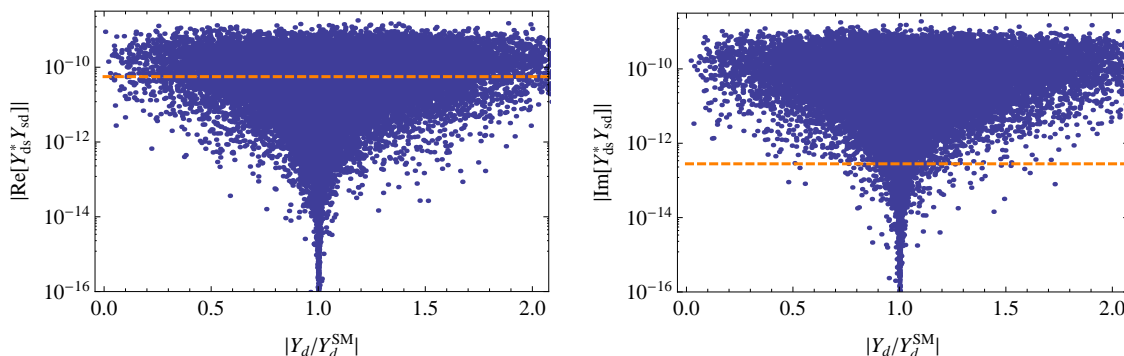


Figure 2. Predictions for the correlation between $|\text{Re}[(\mathbf{Y}^{d*})_{12}(\mathbf{Y}^d)_{21}]|$, $|\text{Im}[(\mathbf{Y}^{d*})_{12}(\mathbf{Y}^d)_{21}]|$ and Y_d . The current experimental constraints from K^0 oscillations are given as the orange dashed lines. See text for details.

[5], as an orange dashed line. We note that we make no special assumption on the phases present in (2.1). It is evident from the plots that, while the constraint on the real part of the couplings has only a marginal constraining power so far, the limit on the imaginary part already allows the conservative estimate

$$0.4 < |Y_d/Y_d^{\text{SM}}| < 1.7. \quad (3.1)$$

While this is not a limit that one can not avoid via fine-tuning the structure of the Yukawa matrices, it however provides us with a rather stringent range where we expect Y_d to lie, given the FCNC data. Let us stress that no other measurement so far exhibits a comparable power in unveiling information on Y_d . Future improvements in FCNC measurements are expected to provide even tighter constraints on Y_d .

Turning our attention to the up-quark sector, we note that the most promising limits from D^0 oscillations $|(\mathbf{Y}^u)_{12}(\mathbf{Y}^u)_{21}|_{\text{exp}} < 7.5 \times 10^{-10}$ [5] are not yet providing strong constraints on Y_u . This is visualized in Figure 3, where we show $|(\mathbf{Y}^u)_{12}(\mathbf{Y}^u)_{21}|$ versus the absolute value of the ratio of the physical up-quark Yukawa coupling Y_u over Y_u^{SM} . The experimental limit is again indicated by the orange dashed line. Here, an improvement of 2-3 orders of magnitude, indicated by the green dot-dashed line, is necessary in order to derive stringent constraints on Y_u .

Finally, to show that our findings are robust with respect to continuous deformations of our setup, we will now study two such possible modifications¹. First, we will raise the scale of the operators by considering $v/\sqrt{2}|(\mathbf{C}_{u,d})_{ij}| = [0, 0.1]$ GeV. Then, in order to show that we do not putting in off-diagonal transitions artificially in an ad hoc way, we are considering $v/\sqrt{2}|(\mathbf{C}_{u,d})_{1,1}| = [0, 5]$ MeV, and the other entries vanishing. The results are given in Figures 4 and 5, respectively, which contain all plots shown so far with an adjusted parameterspace, as discussed above. The plots confirm that the lower contours,

¹Note that the drastic scenario of a full generation of the mass matrices via a different source than the Higgs boson, which would lead to a vanishing $Y_{u,d}$ without necessarily introducing new FCNCs, invalidating our approach, is already highly disfavored from Higgs physics at the LHC.

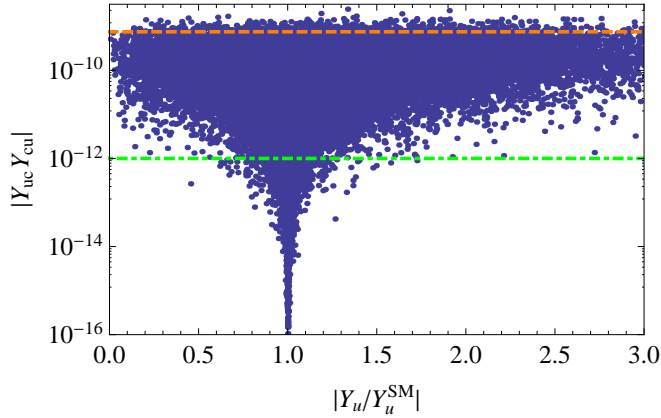


Figure 3. Predictions for the correlation between the off-diagonal transition $|(\mathbf{Y}^u)_{12}(\mathbf{Y}^u)_{21}|$ and $|Y_u/Y_u^{\text{SM}}|$. The current experimental constraint from D_d^0 oscillations is given as an orange dashed line. See text for details.

which provide the important connection between limits on FCNCs and the physical Yukawa couplings $Y_{u,d}$ are rather independent of the particular assumptions on the operators.

4 Conclusions

We have shown how negative search results for FCNCs transitions can be turned into valuable constraints on the first generation Yukawa couplings. While it seems hopeless to get direct information on these couplings from Higgs physics in the near future, given we find no large deviations in Y_b , our method provides the estimate $0.4 < |Y_d/Y_d^{\text{SM}}| < 1.7$. To obtain statements of similar quality for the up-quark sector, some improvements in experimental limits on FCNCs are required.

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References

- [1] M. E. Peskin, “Estimation of LHC and ILC Capabilities for Precision Higgs Boson Coupling Measurements,” arXiv:1312.4974 [hep-ph].
- [2] M. E. Peskin, “Comparison of LHC and ILC Capabilities for Higgs Boson Coupling Measurements,” arXiv:1207.2516 [hep-ph].
- [3] M. Bona *et al.* [UTfit Collaboration], JHEP **0803** (2008) 049 [arXiv:0707.0636 [hep-ph]].
- [4] F. Goertz, in preparation
- [5] R. Harnik, J. Kopp and J. Zupan, JHEP **1303** (2013) 026 [arXiv:1209.1397 [hep-ph]].

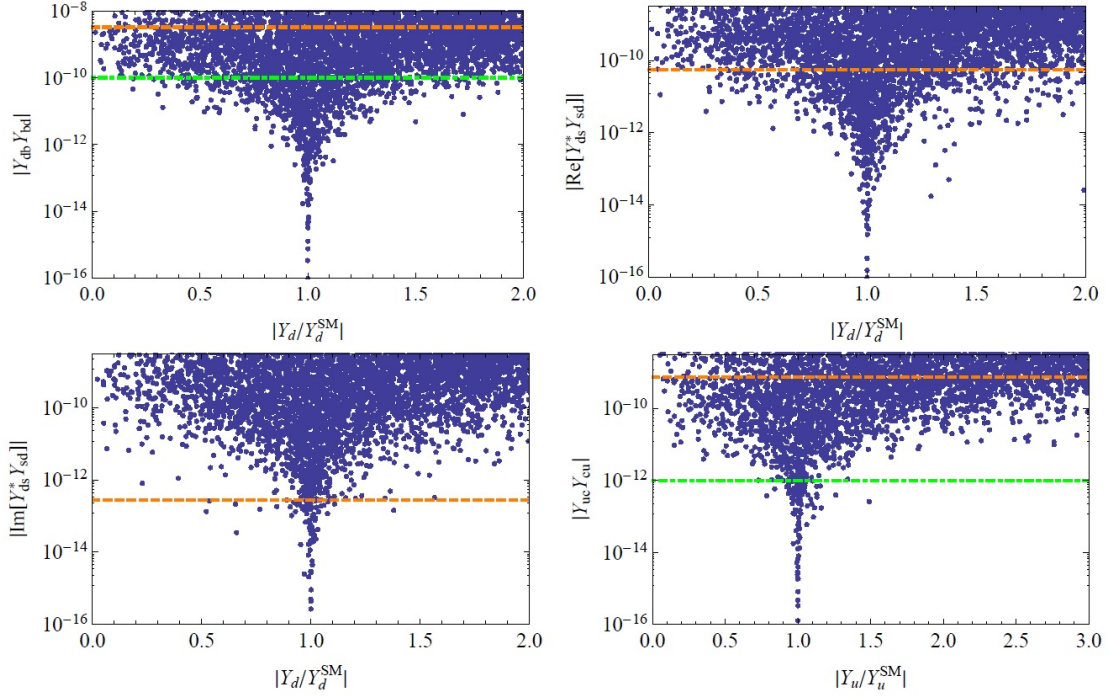


Figure 4. Same plots as before, now with $v/\sqrt{2}|(\mathbf{C}_{u,d})_{ij}| = [0, 0.1]$ GeV, see text for details.

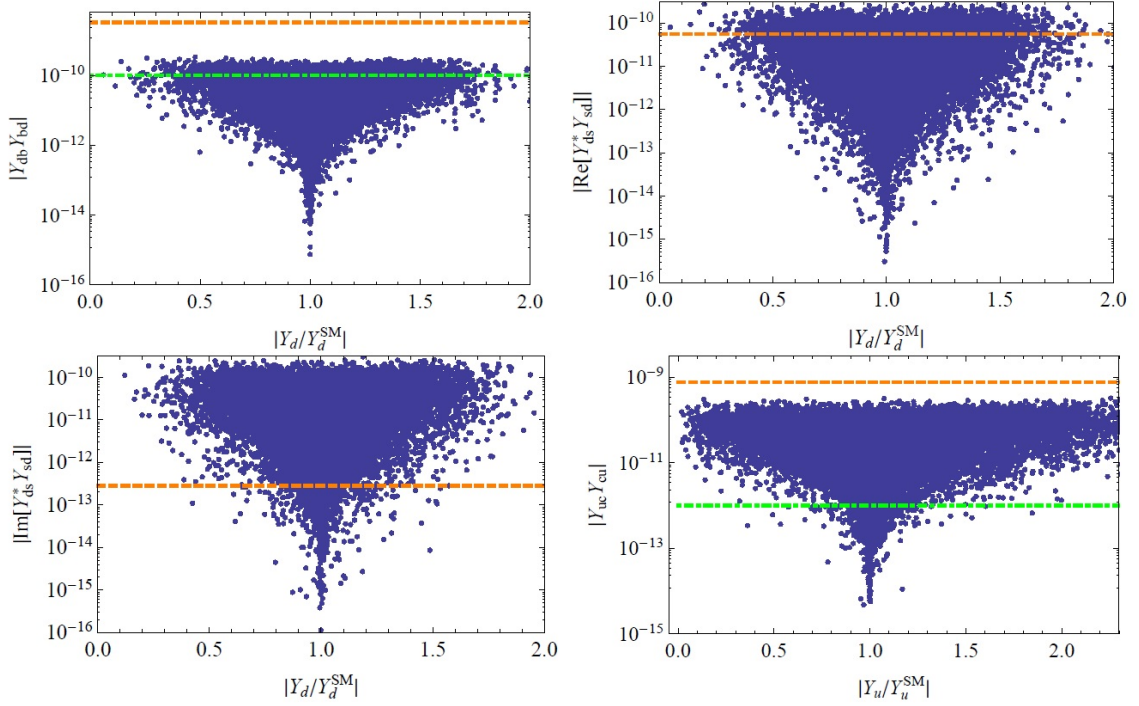


Figure 5. Same plots as before, now with $v/\sqrt{2}|(\mathbf{C}_{u,d})_{1,1}| = [0, 5]$ MeV, see text for details.